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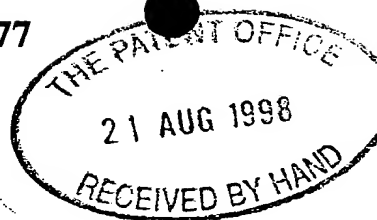
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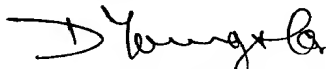
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## **Introduction**

The continuous movement of leukocytes across blood vessel walls to extravascular sites and back to the blood stream is essential for battling foreign pathogens and maintaining homeostasis (1, 2). The migration of T cells through tissues is regulated by adhesion receptors, such as integrins, and by receptors that receive signals provided by pro-inflammatory mediators, such as cytokines, chemokines, and extracellular matrix (ECM<sup>1</sup>)-degrading enzymes (3-6). Here we have examined the interactions between human T cells and two molecules, neutrophil elastase and IL-2, which appear to be involved in T cell activation and migration through tissues.

IL-2 is a 15.5 kDa glycoprotein that participates in the development of inflammation and in the regulation of apoptosis (7, 8). In addition to its pro-activatory and proliferative roles, IL-2 also induces neutrophil adhesion to umbilical vein endothelial cells in a CD18-mediated manner (9) as well as chemotactic responses in T cells, both directly and via regulating their expression of CC chemokine receptors (10, 11). The IL-2 receptor consists of three distinct membrane chains: the  $\alpha$ ,  $\beta$ , and  $\gamma$  chains. The ability of IL-2 to induce T cell activation, differentiation, and proliferation involves the  $\beta$  and  $\gamma$  chains of the IL-2 receptor, which are coupled, through their cytoplasmic domains, to intracellular protein tyrosine kinases and a protein serine/threonine kinase (8, 12). X-ray crystallographic analysis and deletion experiments showed that the sites of IL-2 that bind to the  $\beta$  or  $\gamma$  chains of its receptor are located within the  $\alpha$ -helical and 30 amino acid residues of the N-terminal domain of IL-2 (13). Indeed, anti-IL-2 antibodies that recognize amino acid epitopes in the N-terminal region of IL-2 can inhibit IL-2-induced lymphocyte proliferation. The C-terminal portion of IL-2 and its three Cys residues seem to contribute to the folding and active conformation of IL-2 (13, 14).

The majority of neutrophil elastase (also termed human leukocyte elastase; HLE), which exists as either a membrane-bound or soluble moiety, is produced and released by neutrophils, although small amounts are also produced by macrophages, monocytes, and T cells (15, 16).

Elastase degrades basement membrane and ECM glycoproteins, such as elastin, collagen, fibronectin (FN), as well as molecules expressed on the surface of T cells, e.g., CD4, CD8, and CD2 (17). Recently, two novel functions of neutrophil elastase have been shown: (i) membrane-bound elastase modulates immune cell adhesiveness by interacting with the integrin  $\alpha_M\beta_2$  on neutrophils (18), and (ii) elastase processes IL-8, and thus alters the biological functions of this chemokine (19).

Recently, we have shown that IL-7 interacts with ECM, and that both soluble and matrix-complexed IL-7 induce integrin-mediated adhesive interactions of human T cells with ECM-bound IL-7 and with purified VCAM-1 molecules (21). The biological effects of IL-7 are linked to its interaction with the  $\gamma$ -chain of the IL-2 receptor, which is a tyrosine kinase signal-transducing molecule (22). Also, exposure of T cells (3 to 5 days) to IL-2 was found to induce their migration on collagen (23). Therefore, we examined whether IL-2 can induce T cell adhesion to ECM glycoproteins, whether elastase can process recombinant human IL-2, and whether such putative IL-2 peptides can affect T cell-ECM interactions. We found that IL-2 can indeed induce T cell adhesion to ECM glycoproteins that are otherwise non-adhesive moieties. In addition, we may have identified a group of naturally occurring, elastase-generated IL-2 fractions and peptides capable of inhibiting T cell adhesion and migration.

## Material and methods

**Materials.** The following reagents were obtained as indicated. Recombinant human IL-2 (sp. act.  $18 \times 10^6$  U/mg; Chiron B.V., Amsterdam, The Netherlands); recombinant human IL-7 (sp. act.  $2 \times 10^5$  U/ $\mu$ g; Immunex Corp., Seattle, WA); recombinant human MIP-1 $\beta$  (Pepro Tech, Rocky Hill, NJ); FN (Chemicon; Temecula, CA); BSA, laminin (LN), PMA, and TRITC phalloidin (Sigma Chemical Co., St. Louis, MO); CO-IV (ICN, Costa Mesa, CA); and HEPES buffer, antibiotics, heat-inactivated FCS, sodium pyruvate, and RPMI-1640 (Beit-Haemek, Israel). An anti- $\beta_1$  integrin-specific affinity-modulating 8A2 mAb (24), was donated by Dr. J. M. Harlan (Washington University, Seattle, WA). All protected amino acids, coupling reagents, and polymers were obtained from Nova Biochemicals (Läufelfingen, Switzerland). Synthesis-grade solvents were obtained from Labscan (Dublin, Ireland). HPLC solvents and columns were obtained from Merck (Darmstadt, Germany).

**T cell adhesion assays.** Human T cells were purified from the peripheral blood of healthy donors, and T cell adhesion to immobilized protein substrates was examined as previously described (20, 21). Briefly, human leukocytes were isolated on a Ficoll gradient, washed, and incubated (2 hr, 37°C, 7.5% CO<sub>2</sub>, humidified atmosphere) on petri dishes. The non-adherent cells were then collected and incubated (1 hr, 37°C, 7.5% CO<sub>2</sub>, humidified atmosphere) on nylon wool columns (Novamed Ltd., Jerusalem, Israel). Unbound cells were eluted from the columns by extensive washings. The resulting cell population was always >92% T cells. Intact IL-2 or IL-2-derived peptides (in 50  $\mu$ l) were added to flat-bottomed microtiter wells that had been pre-coated with ECM or ECM proteins (FN or LN; 1  $\mu$ g/well) and blocked with 0.1% BSA. After 4-6 hr at 37°C, the wells were washed and <sup>51</sup>[Cr]-labeled T cells were added to the wells, 10<sup>5</sup> cells/100  $\mu$ l of adhesion medium (RPMI-1640 supplemented with 0.1% BSA, 1% sodium pyruvate, 1% HEPES buffer). The microtiter plates containing the cells were incubated (30 min, 37°C) in a humidified, 7.5% CO<sub>2</sub> atmosphere, and then washed. The adherent cells were lysed, and the resulting supernatants were removed and analyzed in a  $\gamma$ -counter. For each experimental group, the results were expressed as the mean percentage  $\pm$ SD of bound T cells

from quadruplicate wells. To some wells, different concentrations of soluble IL-2 were concomitant with the T cells, and with others, different concentrations of elastase-degraded IL-2-derived fractions, or the corresponding synthetic peptides, were added together with stimulators [PMA (50 ng/ml), IL-7 (50 ng/ml), MIP-1 $\beta$  (20 ng/ml), 8A2 (1  $\mu$ g/ml), mAb anti-CD3 (1  $\mu$ g/ml), or IL-2 (10 units/ml)].

*Chemotaxis assays.* T cell chemotaxis was performed and analyzed as previously described (25). Briefly, the migration of human T cells ( $0.5 \times 10^6$  cells in adhesion medium/well) was examined in a 48-well chemotaxis micro-chamber (Neuro-Probe Inc., Cabin John, MD). The two compartments of the micro-chambers were separated by a FN-coated polycarbonate filter (5  $\mu$ m pore size; OsmonicsProteins Products, Livemore, CA). Where indicated, MIP-1 $\beta$  or IL-2 was added to the lower wells, and the T cells were added to the upper chambers together with the peptides. After incubation (120 min, 37°C, in a humidified, 7.5% CO<sub>2</sub> atmosphere), the filters were removed, fixed, and stained with a Diff-Quik staining kit (Dade, Dürdingen, Switzerland). The number of migrating T cells in five high-power fields (under 500 $\times$  magnification; WILD Microscope, Heerbrugg, Switzerland) was evaluated. For each group the results are expressed as the mean number of cells in one high-power field.

*Purification of elastase and elastase digestion of IL-2.* Neutrophils were isolated from the whole blood of a healthy donor by dextran sedimentation and Ficoll/hypaque gradient centrifugation, as previously described (26). Elastase was isolated by aprotinin-sepharose affinity chromatography, followed by carboxymethyl-cellulose ion exchange chromatography, as developed by Baugh and Travis (26, 27). The purified elastase, which was lyophilized and stored at -20°C until used, was biochemically checked to be entirely free from cross-contamination with cathepsin G (not shown). IL-2 was dissolved in distilled water to yield a 1 mg/ml solution. Lyophilized neutrophil elastase (50  $\mu$ g) was dissolved in 1 ml of PBS and immediately added to the IL-2 solution. The elastase-IL-2 mixture was incubated (12 hr) at 37°C. Aliquots were removed and stored at -20°C until subjected to HPLC separation.



*Reversed-phase HPLC.* Elastase digests of IL-2 were purified with a prepacked Lichrospher-100 RP-18 column (4x25 mm, 5  $\mu$ m bead size), using a binary gradient formed with 0.1 % TFA in H<sub>2</sub>O (solution A) and 0.1% TFA in 75% acetonitrile in H<sub>2</sub>O [(solution B) at t=0 min B=3.5%, at t=5 min B=3.5%, and then, the concentrations began to increase: at t=60 min B=100% (i.e. 75% acetonitrile)]. The flow-rate was constant on 0.8 ml/min. A Spectra-Physics SP8800 liquid chromatography system equipped with an Applied Biosystems 757 variable wave-length absorbency detector was used. The column effluents were monitored by UV absorbency at 220 nm, and the chromatograms were recorded on a Chrome-Jet integrator. Fractions that were 20% or more above valley levels were pooled, roto-evaporated to a minimal volume, and diluted with HPLC grade water. The roto-evaporation and dilution with water step was performed twice in order to remove residual TFA and acetonitrile.

*Amino acid composition of the synthetic peptides and amino acid sequence analysis.* Purified peptide solutions [ $\approx$ 40  $\mu$ g of peptide in 40  $\mu$ l, with 5  $\mu$ g of norvaline (an unnatural amino acid) as an internal standard] were roto-evaporated, hydrolyzed (10°C, 22 hr) in 6 N HCl under vacuum, and analyzed with an amino acid analyzer (HP1090, Palo-Alto, CA). An on-line pre-column ortho-phthalaldehyde (OPA)/Fmoc derivatisation, combined with reversed phase chromatography, was used to determine the amino acid composition of the peptides and the total peptide yield. Without exception, all the peptides yielded excellent analysis ratios of corresponding amino acids deviation from expected values of less than 10%.

Analysis of the elastase-generated IL-2 fractions was performed using a Model 470A gas-phase microsequencer. Phenylthiohydantoin amino acid derivatives were separated on-line by reversed-phase HPLC on a PTH C-18 column (2.1 x 220 mm) using a Model 120A Analyzer (Applied Biosystems, CA).

*Solid phase peptide synthesis.* IL-2-derived peptides were prepared by conventional solid phase peptide synthesis, using an ABIMED AMS-422 automated solid phase multiple peptide synthesizer (Langenfeld; Germany). The 9-fluorenylmethoxycarbonyl (Fmoc) strategy was used for peptide chain assembly, according to the commercial protocol. In each reaction vessel

we used 12.5  $\mu$ mol of Wang resin containing the first, covalently bound corresponding Fmoc C-terminal amino acid (typically, polymer loadings of 0.3-0.7 mmols/g resin were used). Fmoc deprotection was achieved by two consecutive treatments with 20% piperidine in dimethyl formamide, usually 10-15 each min at 22°C, depending on the length of peptide and the Fmoc protected amino acid type. The protecting groups used for the side chain of the amino acids were tert-butyloxycarbonyl for Trp, trityl for Asn, and, tert-butyl-ether for Thr. Usually, coupling was achieved using two successive reactions (typically 20-45 min each at 22°C, depending on the length of peptide and amino acid derivative type) with 50  $\mu$ mol (4 eqv) of N-Fmoc-protected amino acid, 50  $\mu$ mol (4 eqv) of benzotriazole-1-yl-oxy-tris-pyrolidino-phosphonium hexafluorophosphate (PyBop) reagent, and 100  $\mu$ mol (8 eqv) of N-methylmorpholine were all dissolved in DMF. The peptide was cleaved from the polymer by reacting (2 hr, 22°C) the resin with trifluoroacetic acid/H<sub>2</sub>O/triethylsilane; 90/5/5; v/v/v. The solution containing the crude, unprotected peptides was then cooled down to 4°C, precipitated with ether (4°C), and centrifuged (15 min, 3000 rpm, 4°C). The pellet was washed and centrifuged ( $\times 3$ ) with ether, dissolved in 30% acetonitrile in H<sub>2</sub>O, and lyophilized. The lyophilized material was reconstituted in double distilled water before use; only the stock solution, not the diluted material, was stored at -20°C.

*Staining of actin cytoskeleton.* T cells were incubated (18 hr, 37°C, 7.5% CO<sub>2</sub>, humidified atmosphere) in culture media. IL-2 or PMA was then added and incubated for 24 hr to the cell cultures. The T cells were then washed and seeded onto FN-covered cover slips in the presence of either PMA (50 ng/ml), IL-2 (100 U/ml), or IL-2 peptides (0.1 ng/ml). After 1 hr at 37°C, the adherent cells were fixed (3 min) with paraformaldehyde (3%) and Triton X-100 (0.5%), washed, and fixed (20 min) again with paraformaldehyde (3%). The fixed adherent cells were washed, treated with TRITC phalloidin, and washed again. Photographs ( $\times 1000$  magnification) were then taken.

## Results

*Induction of the adhesion of T cells to ECM, FN, LN, and CO-IV by IL-2.* Some cytokines induce adhesion of leukocytes to endothelial cells, the underlying basement membrane, and to the ECM (3, 4, 6, 20, 21). Therefore, we examined the ability of soluble IL-2 to induce adhesion of human T cells to ECM, FN, LN, and CO-IV. The results indicated that IL-2 induced T cell adhesion to FN, LN, and CO-IV (Figure 1A), as well as to intact ECM (Figure 1B). Note that the adhesion of T cells to LN induced by IL-2 was lower than that induced to the other ECM glycoproteins. When T cells were activated only with PMA,  $45 \pm 4.4\%$  of them adhered to immobilized ECM and ECM glycoproteins (not shown). IL-2-induced T cell adhesion to the ECM glycoproteins was inhibited by anti-human  $\beta_1$  integrins mAb (not shown), which suggests that the pro-adhesive effects of IL-2 were induced via cell surface-expressed integrins. However, under our experimental conditions, IL-2 did not alter the T cell surface expression of  $\beta_1$  integrins (not shown). Thus IL-2, in addition to other pro-inflammatory mediators, appears to regulate the adhesiveness of resting human T cells to immobilized ECM and ECM glycoproteins.

*The effects of IL-2 fragments obtained by elastase degradation on the interaction of T cells with FN.* We have assumed that the degradation of IL-2 can occur in the inflamed milieu, where both cytokines, such as IL-2, and proteolytic enzymes, such as neutrophil elastase, are present. We also hypothesized that, in contrast to the intact IL-2 molecule, certain portions of IL-2 can abrogate the adhesiveness of activated T cells to ECM ligands. Hence, elastase and soluble IL-2 were incubated together at physiologic conditions. HPLC analysis of the elastase-degraded IL-2 revealed at least 8 peaks of IL-2, each of which represented at least one low molecular weight protein fragment (Figure 2).

Next, we examined the ability of the HPLC-purified IL-2 fractions, which were generated by elastase-degradation, to inhibit soluble IL-2-induced interactions of T cells with FN. We chose to investigate the major peaks of HPLC-purified, elastase-degraded fractions of IL-2. Fractions 2, 7, and 8 inhibited the adhesion of T cells to immobilized FN in a dose-dependent

and statistically significant fashion, whereas fractions 4 and the HPLC buffer did not (3). Thus, certain IL-2 fragments, obtained by neutrophil elastase-processing of the cytokine, can inhibit IL-2-induced adhesion of T cells to FN.

*The effect of synthetic peptides, with putative amino acid compositions corresponding to fractions 2 and 8, on IL-2-induced T cell adhesion to FN.* Next, the primary sequence of fractions 2 and 8 were analyzed by gas-phase chromatography since these elastase-generated fractions of IL-2 appeared to contain adhesion-suppressive peptides. Our analysis revealed that fragment 2 contained an Ile-Val-Leu (IVL; IL-2-112-114) and an Arg-Met-Leu-Thr (RMLT; IL-2-58-61) peptide, whereas fragment 8 contained a Glu-Phe-Leu-Asn-Arg-Trp-Ile-Thr (EFLNRWIT; IL-2-136-143) octa-peptide. These three peptides were synthesized, and their effects on IL-2-induced T cell adhesion to FN were studied. The IVL, RMLT, and EFLNRWIT, inhibited, in a dose-dependent manner, the adhesion of IL-2-activated T cells to FN; the RMLT is apparently the most potent inhibitor (Figure 4A). Maximum inhibition was achieved with about 0.1 pg/ml (0.2 pM) for RMLT, and 1 pg/ml of either IVL or EFLNRWIT (2.91 and 0.92 pM, respectively). The inhibitory dose-response curves of IVL and EFLNRWIT are similar to those of the HPLC fractions 2 and 8, respectively, from which they were derived.

To examine the specificity, on the biological and chemical levels, of the inhibition of T cell adhesion by the elastase-generated, synthetic IL-2 peptides, we synthesized the three IL-2 peptides in their inverse amino acid sequences, LVI, TLMR, and TIWRNLFE, and then tested their effects on IL-2-induced T cell adhesion to FN. The results, shown in Figure 4B, indicate that none of these peptides, tested in a broad range of dosages, interfere with T cell adhesion. Thus, the anti-adhesive effects of IVL and EFLNRWIT peptides of IL-2 appear to be due to their direct biological effect on responding lymphocytes.

Do the IL-2 peptides, IVL, RMLT, and EFLNRWIT have to be present during the entire period of the assay to exert their inhibitory effects? The results, shown in Figure 4C, indicate that most of the anti-adhesive effects of the three peptides persevered even if these peptides (at 1

pg/ml) were removed from the T cells prior to their activation with IL-2 and seeding onto the FN-coated surfaces. Apparently, their prolonged inhibitory potential may involve active intracellular signaling pathways. These results suggest that the IL-2 peptides neither exert their inhibitory activities on T cell adhesion to FN via binding to the ECM protein, nor to FN-specific  $\beta_1$  integrins expressed on the adhering T cells.

*IVL, RMLT and EFLNRWIT inhibit T cell adhesion to LN, CO-IV and FN.* The next experiment was designed and performed to verify that the three IL-2-derived peptides indeed affect T cell interactions with ECM glycoproteins other than FN. T cells were pre-exposed to the three peptides (at 10 pg/ml), and then activated with IL-2. The treated cells were then added to microtiter wells coated with CO-IV, LN, and FN. The results, shown in Figure 5, indicate that both IVL, RMLT, and EFLNRWIT inhibit T cell adhesion to the three major cell-adhesive glycoproteins of the ECM (Figure 5), suggesting that the elastase-generated IL-2 peptides exert their inhibitory effects over different subsets of  $\beta_1$  integrins.

*IVL and EFLNRWIT inhibit T cell chemotactic migration induced by IL-2 or MIP-1 $\beta$ .* Immune cell migration is the outcome of a subtle biological equilibrium existing between adhesion and detachment events. Lymphocyte adhesion to the subendothelial ECM and subsequent migration are two active processes that can overlap, but are not mutually dependent events. Adhesion and migration may depend on the ability of the T cells to continuously integrate different pro- and anti-adhesive signals via their versatile receptors for ECM, chemokines, cytokines, and possibly, also antigenic moieties (1, 2). In fact, it has been recently shown that transient (i.e. low affinity) rather than prolonged interactions between integrins and the ECM favor IL-4-induced B cell migration, and not adhesion (28). Therefore, we next examined the effects of the IVL, RMLT, and EFLNRWIT peptides (at 1 pg/ml) on the IL-2- and MIP-1 $\beta$ -induced T cell chemotaxis through FN-coated polycarbonate membranes. The gradient generated by MIP-1 $\beta$  and IL-2, which were placed in the lower compartment of the 48-well chemotaxis apparatus, induced a marked T cell migration through FN-coated membranes, which was about 3 to 4-fold higher than the control (Figure 6). Both IVL, RMLT, and

EFLNRWIT markedly ( $P < 0.01$ ) inhibited T cell migration towards IL-2, by about 30, 90, and 60%, respectively. However, although the IVL peptide, and to a lesser degree also the RMLT peptide, markedly inhibited (80% and 60%, respectively) T cell chemotaxis towards MIP-1 $\beta$ , the EFLNRWIT showed only a limited inhibitory effect on the chemokine-induced T cell chemotaxis. Thus, in addition to the capacity of the IVL and EFLNRWIT peptides to inhibit T cell-ECM adhesion, they seem to inhibit T cell migration through FN in response to a diffusible gradient produced by IL-2 or MIP-1 $\beta$ .

*Inhibition by the IVL and EFLNRWIT peptides of T cell adhesion to FN induced by various pro-inflammatory mediators and by mAb specific for molecules expressed on T cells.*

The preceding chemotaxis experiments indicated that the IVL and EFLNRWIT peptides can inhibit T cell adhesion and migration through FN barriers induced not only by IL-2, but also by the chemokine MIP-1 $\beta$ . Therefore, in an attempt to further understand the possible physiological relevance of such phenomena, we examined the ability of these peptides to inhibit the adhesion to FN of T cells stimulated by modes other than IL-2. T cell adhesion to FN can be up-regulated by physiological activators, such as IL-7 (21), MIP-1 $\beta$  (20), and via the CD3 complex, as well as by non-physiological stimuli of integrin avidity, such as PMA (29), and a  $\beta_1$  integrin-specific activating mAb, 8A2 (24). This mAb up-regulates the endothelial cell and ECM ligand-binding activities of the  $\alpha_4\beta_1$  and  $\alpha_5\beta_1$  integrins by binding to their cell surface-expressed sites, and thus converting these non-binding integrins to their high affinity, ligand-occupying forms (24).

At 10 pg/ml, both EFLNRWIT and IVL inhibited T cell adhesion to FN that was induced by various stimulators of T cells and modulators of the  $\beta_1$  integrin functions tested (Figure 7). However, at 0.1 pg/ml, EFLNRWIT did not inhibit the PMA and 8A2-induced adhesion, and the IVL peptide did not inhibit PMA, 8A2, and the anti-CD3 mAb-induced T cell adhesion to FN, which indicates that these modes of activation are less susceptible to IL-2-derived peptide-induced suppression than IL-2-mediated activation. In experiments similar to those shown in Figures A and B, the control peptides (LVI and TIWRNLFE) did not affect T cell adhesion to FN induced by the indicated activators (data not shown). Hence, EFLNRWIT and IVL

apparently inhibit T cell adhesion to the FN component of ECM via a common intracellular event that is linked to the regulation of the avidities and affinities of  $\beta_1$  integrins, and therefore, to their ligand recognition and binding.

*Inhibition of the reorganization of the actin cytoskeleton in FN-attached activated T cells by the EFLNRWIT peptide.* The adhesion of immune cells to ECM is dependent on the sequestering of the cytoplasmic domains of integrins in focal adhesion sites, together with actin-containing microfilament bundles (30-32). Therefore, we examined the effect of EFLNRWIT on the morphologies of adherent T cells. The T cells were activated with IL-2 or PMA, treated with the IL-2 peptides, and seeded onto FN-coated cover slips. After incubation and fixation, the actin cytoskeleton of attached T cells was stained with TRITC-conjugated phalloidin. The morphologies of FN-bound IL-2- and PMA-activated T cells (Figure 8, A and B) were markedly different from those of non-activated lymphocytes (Figure 8E); the activated T cells appeared spread, and their actin cytoskeleton performed distinct structures typical of ECM-adherent cells. The EFLNRWIT peptide inhibited the redistribution of the actin skeleton in both the IL-2- (Figure 8C) and PMA-treated (Figure 8D) FN-adherent T cells. Control peptides (LVI, TLMR, and TTWRNLFE) did not inhibit the actin reorganization of the activated T cells (not shown). Hence, the adhesion-inhibiting activity of the IL-2-derived peptide EFLNRWIT, similar to the IVL peptide (data not shown), appears to involve inhibition of the redistribution of the actin cytoskeleton, and therefore, changes in cell shape and spreading.

## Discussion

Certain pro-inflammatory mediators can exert their migratory effects in solution or while bound to components of blood vessel walls (3, 6, 33). The binding of these mediators to components of tissue barriers probably ensures the mediators' persistence and effectiveness in the vicinity of the inflammation-mediating immune cells themselves. This transient binding also creates migratory paths, which consist of cytokine gradients that affect the movements of leukocytes through vessel walls and the ECM (3, 4). IL-2 and elastase are perhaps prominent mediators of leukocyte extravasation and migration from the vasculature through the ECM to sites of inflammation. Besides inducing activation and proliferation of T cells, IL-2 can increase the expression of the CC-CKR1 and CC-CKR2 chemokine receptors on CD45<sup>RO</sup> T lymphocytes (11). This suggests that IL-2 may participate in the recruitment of antigen-primed T cells to sites of immune reactions. We have shown that soluble human IL-2 can induce T cell adhesion to intact ECM and several major ECM-glycoproteins. IL-2 can also associate directly with ECM ligands (dissociation constant in the range of 1  $\mu$ M), and this association facilitates the adhesion of resting human T cells to lower concentrations of the ECM-complexed cytokine (not shown).

We then hypothesized that, in contrast to the pro-adhesive effects of the intact IL-2 molecule, certain short IL-2-derived peptides, which may occur *in vivo*, can inhibit the interactions of T cells with ECM, and that this interference is independent of the peptides' effects on the activation of T cells by IL-2. We also assumed that such moieties of IL-2 can prevent the arrival of T cells at inflamed sites. Neutrophil elastase was a likely candidate for the physiological production of these inhibitory peptides. Elastase, which is enzymatically versatile (17, 18), can be expressed and secreted by the migrating T cells themselves (16), and can transmit mitogenic stimulations from the environment into the responding T cells (15). In fact, LPS- and fMLP-activated neutrophils express catalytically-active membrane-bound elastases, proteinase 3 and cathepsin G on their cell surfaces, which ensure the presence of these enzymes at the leading edge of the tissue-invading cells (34, 35). Other matrix-degrading



enzymes, such as matrix metalloproteinases, cathepsin B, the urokinase-type plasminogen activator, and plasmin can also be bound on the cell surfaces of fibroblasts and migrating cells (5, 36). An important feature of elastase is its ability to act in both soluble and immobilized forms, since a migrating immune cell that expresses immobilized elastase may encounter matrix-bound IL-2, among other cytokines. We have found that the processing of recombinant IL-2 by elastase results in the production of at least eight different bi-products. Three of these products (present in HPLC fractions 2, 7 and 8) inhibited IL-2-mediated T cell adhesion to FN. Amino acid composition analysis and amino acid sequencing revealed that fraction 2 contained the tripeptide IVL (IL-2-112-114) and the tetra-peptide RMLT (IL-2-58-61), and fraction 8 the octapeptide EFLNRWIT (IL-2-136-143). The RMLT peptide appeared to be located within the IL-2-binding site of  $\alpha$  chain of the IL-2R, whereas the IVL and EFLNRWIT are located at sites far from the receptor-binding sites of IL-2 (7, 8). These peptides, at a pM range of concentrations (i.e. 0.01 to 1 pg/ml), inhibited the IL-2, as well as MIP-1 $\beta$ -induced chemotaxis of human T cells through FN-coated polycarbonate membranes.

The chemoattractive capacity of IL-2 in T cell migration studies *in vitro* has been shown by using bare polycarbonate filters or CO- or Matrigel-coated membranes as immobilized substrates. T cell migration in these systems was proved to be IL-2R  $\beta$  chain-specific and depended on the activities of the matrix-degrading gelatinases (10, 37, 38). Here, in addition to their anti-migratory effects, both peptides of IL-2 inhibited T cell adhesion to FN induced by various physiological and non-physiological stimuli. Nevertheless, both IVL, RMLT, and EFLNRWIT, at 1 to 100 pg/ml, did not interfere with either PHA- or IL-2-mediated proliferative responses of human T cells, nor did these peptides inhibit the secretion of TNF $\alpha$  and IFN $\gamma$  from these proliferating cells (not shown). Moreover, the inversely synthesized molecules, LVI, TLMR, and TITWRNLFE, did not inhibit T cell adhesion to FN. Thus, the migration- and adhesion-suppressive capabilities of IVL, RMLT, and EFLNRWIT are specific, and are not due to toxic cell death.

How do the elastase-derived IL-2 peptides exert their inhibitory functions? We demonstrated that the three peptides do not have to be present during the entire period of the adhesion assay, since their anti-adhesive effect was apparent even after their removal from the assay prior to T cell activation with IL-2. This finding also implies that the IVL, RMLT, and EFLNRWIT peptides do not function by interacting with putative cell-adhesive epitopes present on the tested ECM glycoproteins. The existence and the activity of putative T cell surface-expressed receptors specific to the IL-2 peptides described here require additional study. Current data from our laboratory indicate that the IL-2 peptides, when used in relatively high concentrations (i.e. >1 ng/ml), inhibit a chemokine-induced influx of  $\text{Ca}^{+2}$  ions into the treated human T cells. The lymphocytes thus treated are then rendered non-responsive to various pharmacological and immunological activators of adhesion (A. Ariel, *et al.*, in preparation). However, it seems to be highly unlikely that two of these peptides (IVL and EFLNRWIT) exert their biological functions by interacting with the IL-2R subunits or by directly binding to  $\beta_1$ -specific integrins. The IL-2 peptides interfered with different modes of T cell activation, leading to their adhesion to the tested matrix proteins. Moreover, both peptides, used in a pM range of concentrations, appear to block T cell adhesion not only to FN, mediated predominantly via the  $\alpha_4\beta_1$  and  $\alpha_5\beta_1$  integrins, but also to LN; T cell adhesion to LN was mediated primarily through the  $\alpha_3\beta_1$  and  $\alpha_6\beta_1$  integrins. Interesting, however, is the fact that the RMLT peptide resides within the IL-2R $\alpha$ -binding site of IL-2; two residues, Arg-58 and Phe-62, which are present within and adjacent to this peptide, respectively, were shown to be critical for IL-2-IL-2R interactions (13, 39). Therefore, it will also be interesting to examine whether the degradation of IL-2 by elastase produces compounds that can interfere with IL-2 binding to its receptor, and the biological outcome of such molecular interactions.

The ability of EFLNRWIT (as well as the other two IL-2 peptides, not shown) to inhibit the PMA- and IL-2-induced T cell adhesion to FN is probably linked to its ability to block the reorganization of the intracellular actin cytoskeleton. Integrin-cytoskeleton associations can modulate cell adhesion to ECM ligands and cell spreading at areas of cell contact with the

substratum and the micro-clustering and redistribution of  $\beta_1$  integrins on the cell surface at sites of focal adhesion located at the ends of the actin fibers (29, 31, 40). In fact, actin cytoskeleton reorganization, occurring after activation of leukocytes via a Rho-dependent activation of the  $\zeta$  isoform of protein kinase C (41, 42), is linked to leukocyte emigration. Similar observations were noted for T cell activation by IL-2 (and PMA) and attachment to FN. Although the intracellular mechanisms of action of the elastase-generated fractions and peptides have not yet been determined, we postulate that these proteins effect the adhesion and migration of T cells within the ECM by active inhibition of intracellular signal transduction pathways linked to cytoskeleton organization, resulting in inhibiting the micro-clustering and association of integrins with cytoskeletal elements.

Our findings imply that the tissue-invading T cells themselves can dynamically regulate their functions. Both adhesion- and migration-promoting stimuli (i.e. intact IL-2) and suppressive bi-products of inflammatory mediators can be present, although not necessarily simultaneously, within the inflammatory milieu (43). At the early stages of inflammation, both IL-2 and elastase may function concomitantly to activate T cells to penetrate tissues. Later, the degradation peptide products of IL-2, generated by elastase, may inhibit T cell migration, inhibit the co-stimulatory effects of IL-2 and other mediators, and probably signal the termination of the inflammatory reaction.

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### Figure legends

*Figure 1. Induction of T cell adhesion to FN, LN, CO-IV (A) and ECM (B) by IL-2.* [ $^{51}\text{Cr}$ ]-Labeled human T cells were seeded onto FN, LN, CO-IV, and ECM-coated microtiter wells together with IL-2. After 30 min at 37°C, non-adherent T cells were removed, the adherent cells were lysed, and the percentage of T cells that had adhered was determined. One experiment representative of four.

*Figure 2. Chromatogram of IL-2 fractions obtained upon elastase proteolysis.* IL-2 (1 mg/ml) was incubated (12 hr, 37°C) with neutrophil elastase (50  $\mu\text{g}/\text{ml}$  in PBS). The resulting enzymatic digests were purified by HPLC. Fraction 1 consisted of salts used for the separation procedure. One experiment representative of three.

*Figure 3. Effects of IL-2 fractions, generated by elastase degradation, on the IL-2-induced adhesion of T cells to FN.* IL-2 (10 U/ml)-stimulated [ $^{51}\text{Cr}$ ]-labeled T cells were seeded, in the presence or absence of elastase-generated IL-2 protein products, onto wells coated with FN. After 30 min at 37°C, non-adherent T cells were removed, and the percentage of adhered cells was determined. One experiment representative of six.

*Figure 4. Specific inhibition, by elastase-generated fractions 2 and 8 of IL-2 and by their synthetic peptides, of IL-2-induced T cell adhesion to FN.* A. T cell adhesion to FN in the presence of IL-2 fractions and peptides. B. The effects on T cell adhesion to FN of the inversely synthesized IL-2 peptides. T cells were activated with IL-2 (10 U/ml) and seeded onto FN-coated wells in the presence of IL-2, fraction 2, fraction 8, or IL-2 peptides. C. Effects of pre-treatments of T cells with IL-2 peptides on the subsequent IL-2-induced T cell adhesion to FN. T cells used were untreated or pre-treated with the indicated peptides (1  $\mu\text{g}/\text{ml}$ ; 60 min, 37°C, 10%  $\text{CO}_2$ , humidified atmosphere), washed ( $\times 2$ ), exposed to IL-2, and seeded onto the FN coated wells. After 30 min at 37°C, T cell adhesion was measured. One experiment representative of five.

*Figure 5. Inhibition by the IL-2 peptides of T cell adhesion to LN, CO-IV and* cells were pre-treated with the indicated IL-2 peptides (10 pg/ml, 30 min, 37°C, 10% CO<sub>2</sub>, humidified atmosphere) and then with IL-2 (10 U/ml). The T cells were then seeded onto microtiter wells which were pre-coated (1 µg/well) with the various ECM glycoproteins. T cell adhesion was measured 30 min later.

*Figure 6. Inhibition of IL-2-induced T cell migration through FN by EFLNRWIT and IVL.* T cells were pre-treated with IL-2 peptides (1 pg/ml) or buffer alone and then placed in the upper wells of a chemotaxis chamber, in which IL-2 (10 U/ml) or MIP-1β (10 ng/ml) had been added to the lower compartment. T cell migration towards the chemotactic sources was assessed after 2 hr. One experiment representative of four.

*Figure 7. Inhibition by EFLNRWIT (A) and IVL (B) of T cell adhesion to FN, induced by various activators.* Labeled T cells were seeded onto FN-coated wells, in the presence of IL-2 (10 U/ml), IL-7 (50 ng/ml), MIP-1β (20 ng/ml), PMA (50 ng/ml), 8A2 mAb (1 µg/ml), or anti-human CD3 mAb (1 µg/ml). The IL-2-derived peptides, IVL or EFLNRWIT were also present in some wells. After 30 min at 37°C, non-adherent T cells were removed by washing, the remaining adherent cells were lysed, and the percentage of T cells that had adhered was determined. One experiment representative of four.

*Figure 8. Inhibition by the EFLNRWIT peptide of the spreading and redistribution of the actin cytoskeleton in IL-2- and PMA-activated, FN-adherent T cells.* T cells were activated (48 hr) with IL-2 (50 U/ml). The T cells were then washed and seeded onto FN-coated cover slips, in medium alone (E), in the presence of IL-2 (100 U/ml; A and C), or PMA (50 ng/ml; B and D), or EFLNRWIT (10 pg/ml; C and D). After incubation, the intracellular actin filaments of the fixed FN-attached T cells were stained. Original magnification ×1000.

ABSTRACT

NOVEL PEPTIDES

Migration of inflammatory cells requires cell adhesion and their subsequent detachment from the extracellular matrix (ECM). Leukocyte activation and migration must be terminated to stop inflammation. Here we report that IL-2 enhances human T cell adherence to laminin, collagen type IV, and fibronectin (FN). In contrast, neutrophil elastase, an enzyme activated during inflammation, degrades IL-2 to yield IL-2 fractions that inhibit IL-2-induced T cell adhesion to FN. The amino acid composition of two of these IL-2 fractions, which appear to block T cell adherence to FN, were analyzed, and three peptides were consequently synthesized. The three peptides: IVL, RMLT, and EFLNRWIT, but not the corresponding inversely synthesized peptides, inhibited T cell adhesion to FN induced by a variety of activators: IL-2, IL-7, MIP-1 $\beta$ , PMA, as well as anti-CD3 and - $\beta_1$  integrin-activating mAb. Moreover, these IL-2 peptides inhibited T cell chemotaxis via FN-coated membranes induced by IL-2 and MIP-1 $\beta$ . Inhibition of T cell adherence and migration apparently involves abrogation of the rearrangement of the T cell actin cytoskeleton. Thus the migrating immune cells, cytokines, and the ECM can create a functional relationship in which both inflammation-inducing signals and inhibitory molecules of immune responses can reciprocally co-exist; the enzymatic products of IL-2 may serve as natural feedback inhibitors of inflammation.



Figure 1 (A, B)

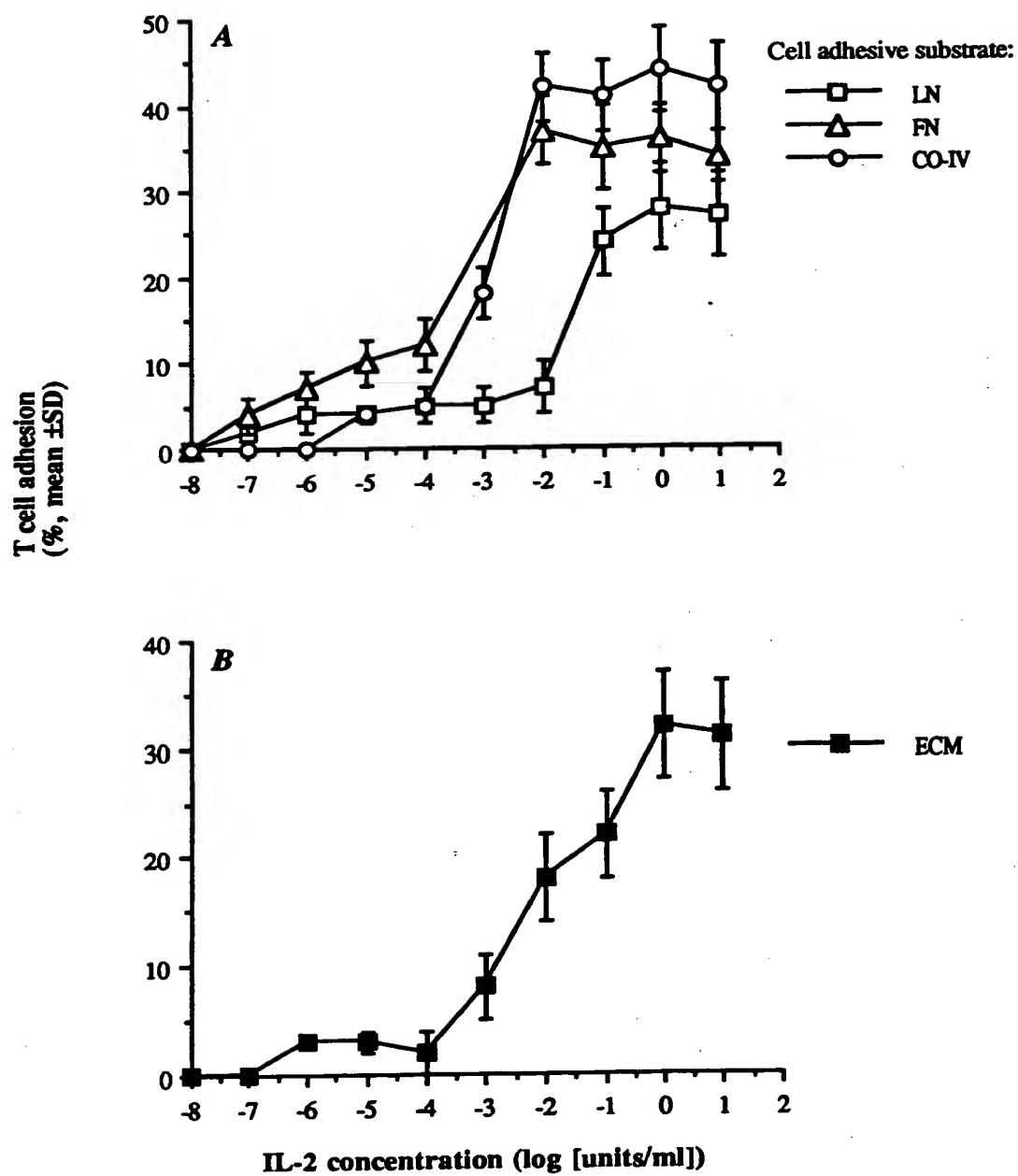




Figure 2

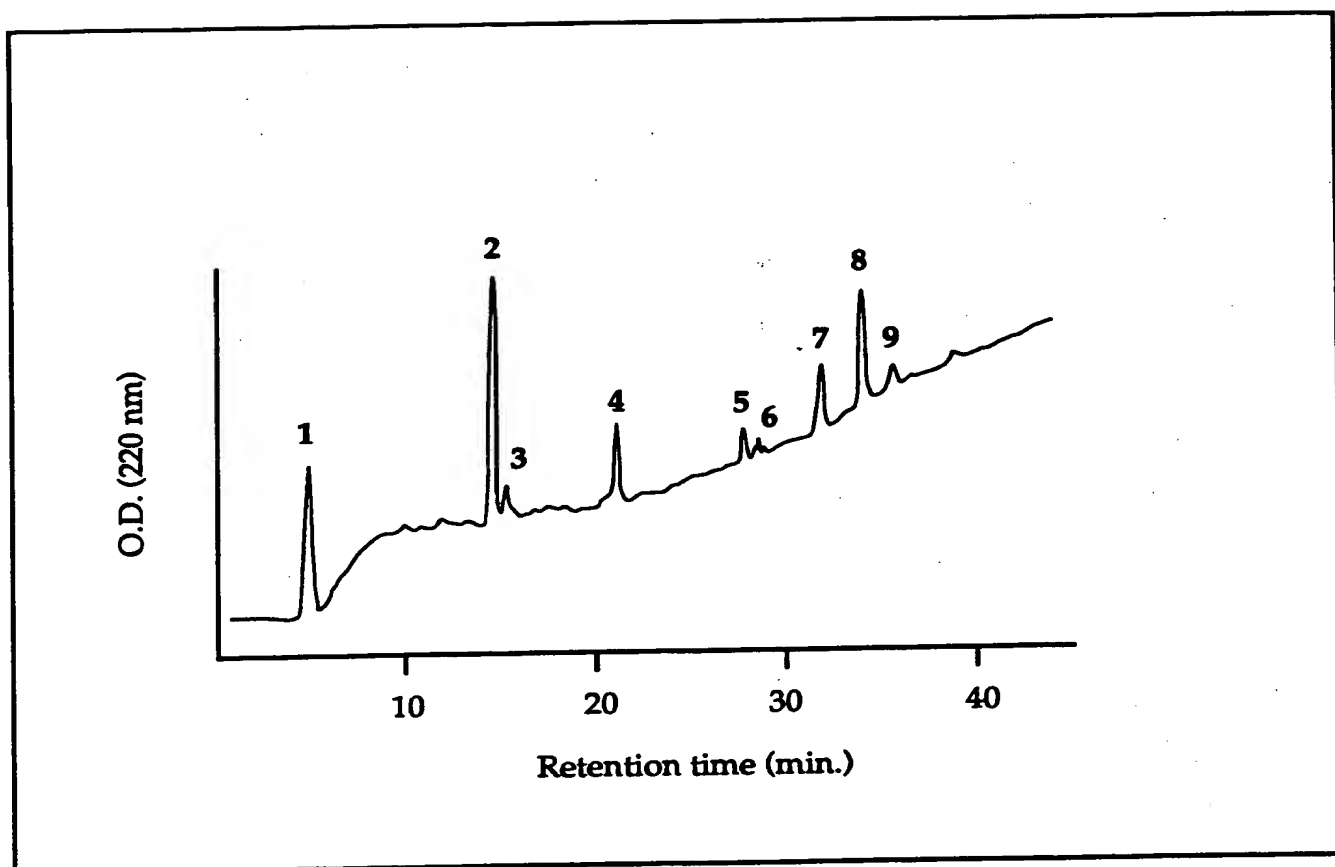






Figure 3

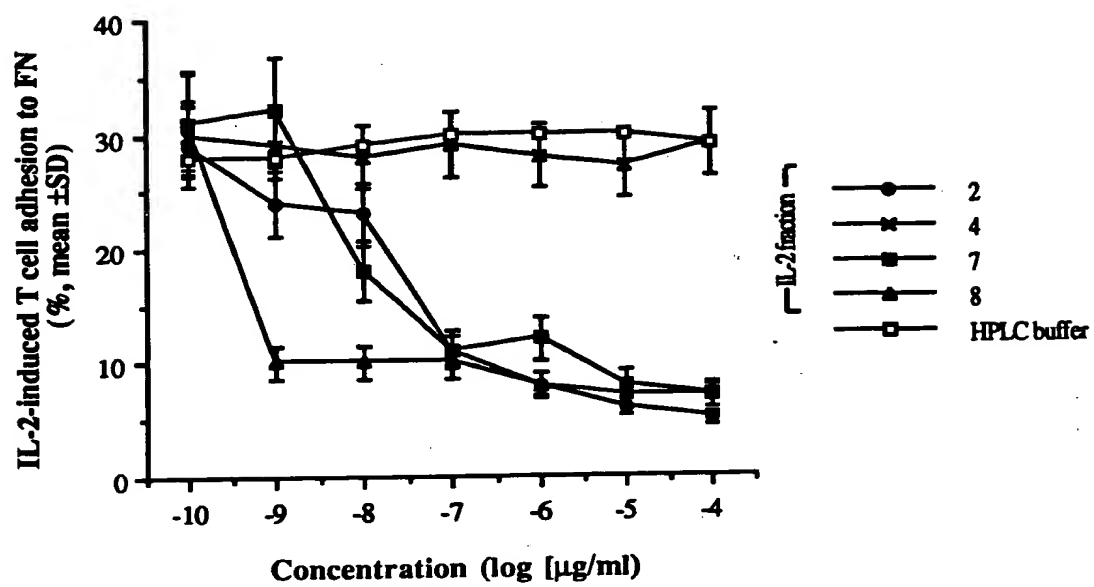




Figure 4

IL-2 induced T cell adhesion to FN  
(%, mean  $\pm$ SD)

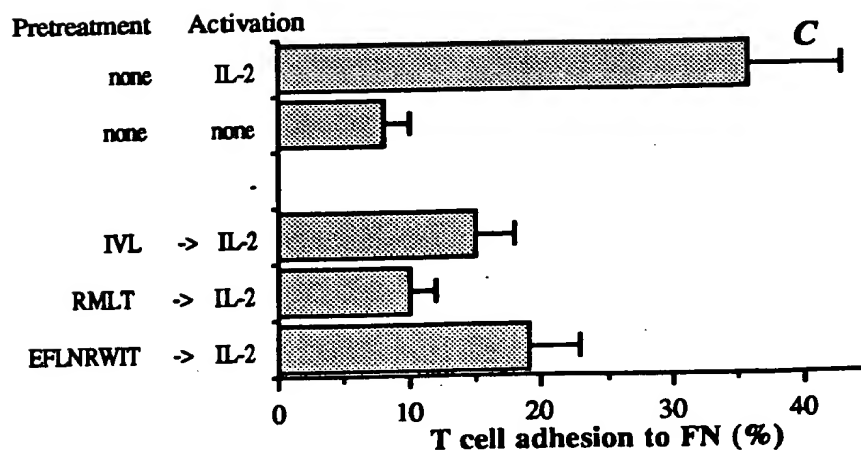
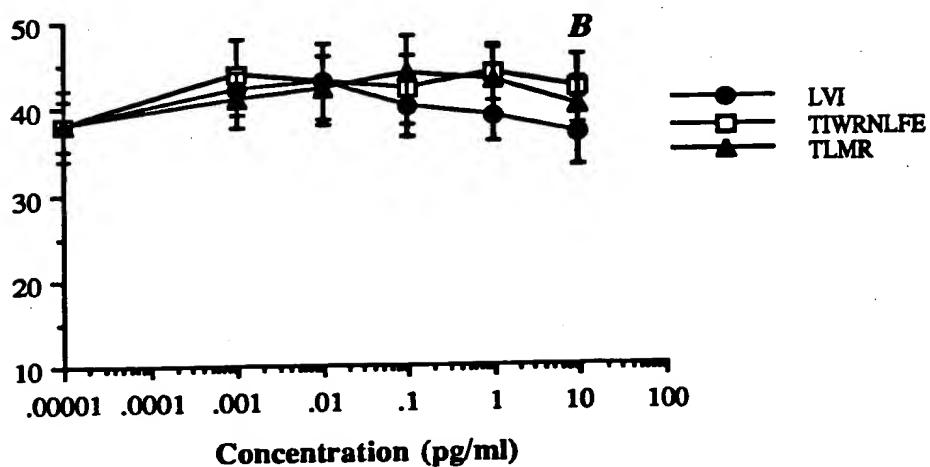
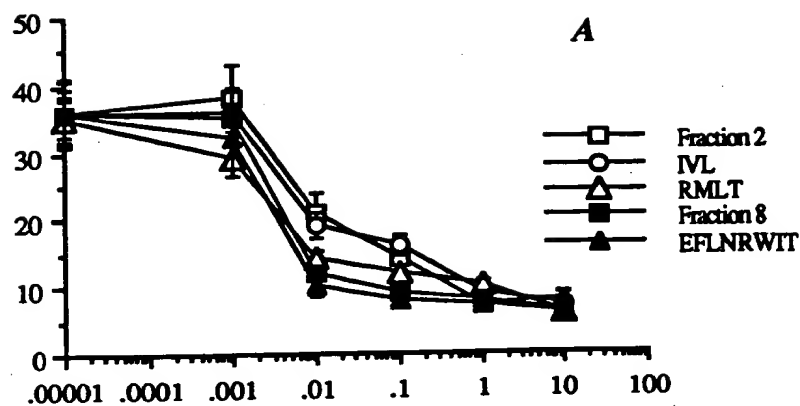




Figure 5

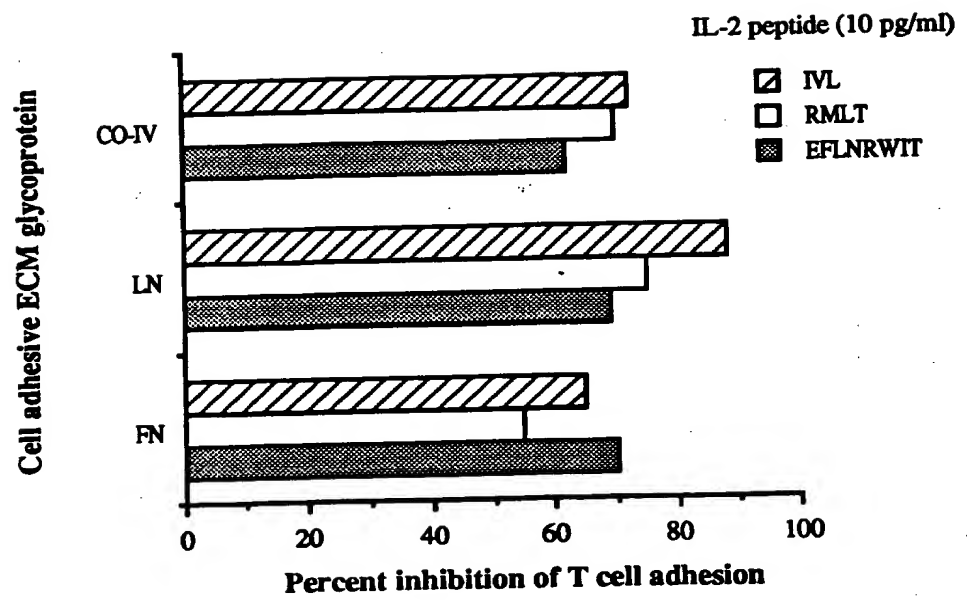




Figure 6

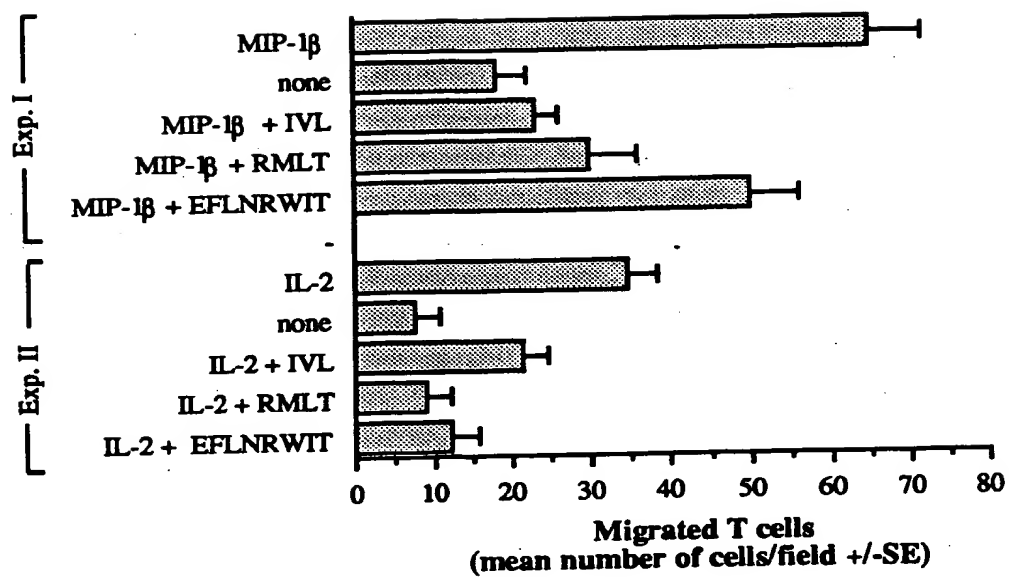






Figure 7

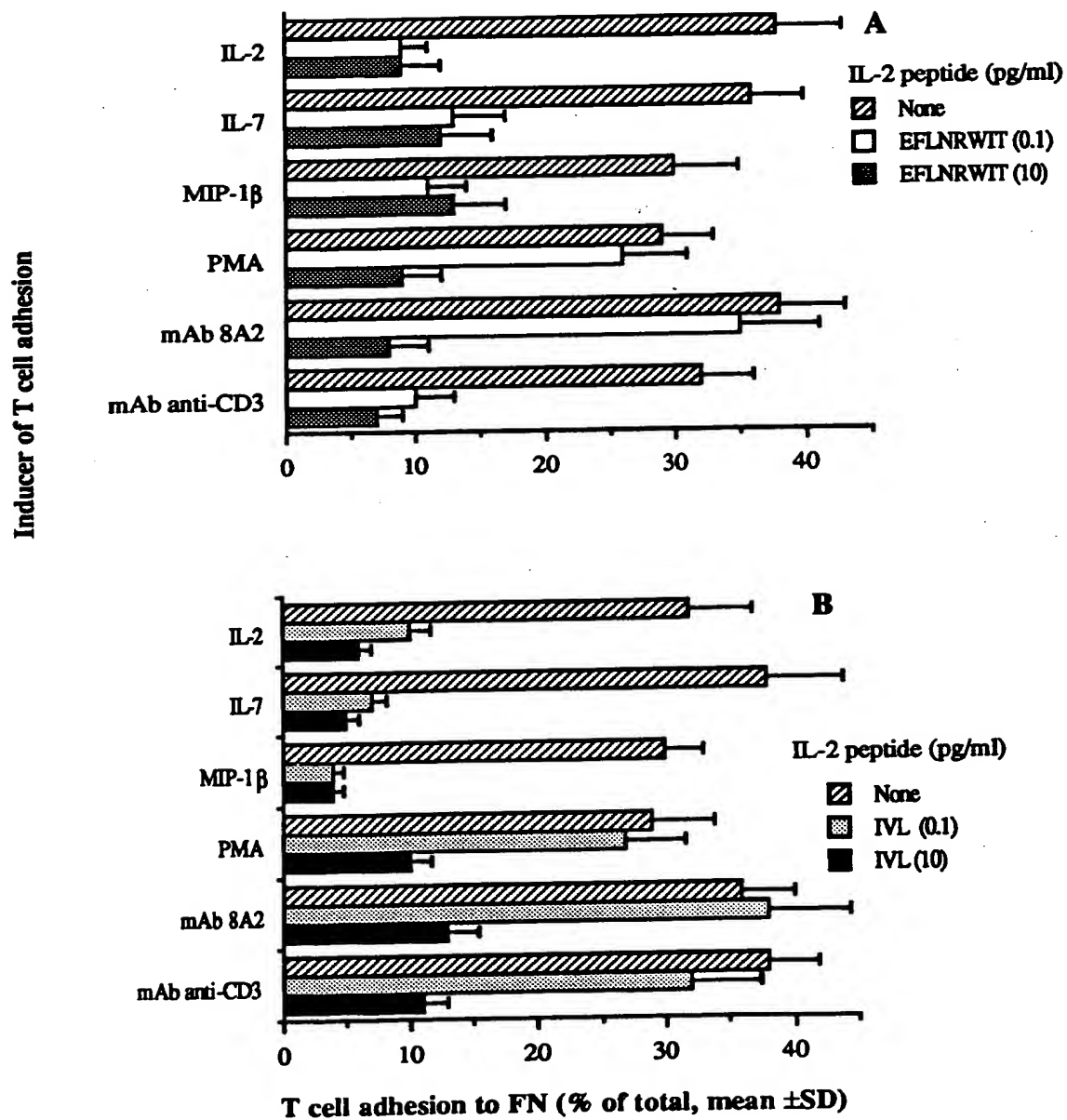




Figure 8

